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Investigation of Methods for Selectively Reinforcing Aluminum and Aluminum-Lithium Materials

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Abstract

Several studies have indicated that selective reinforcement offers the potential to significantly improve the performance of metallic structures for aerospace applications. Applying high-strength, high-stiffness fibers to the high-stress regions of aluminum-based structures can increase the structural load-carrying capability and inhibit fatigue crack initiation and growth. This paper discusses an investigation into potential methods for applying reinforcing fibers onto the surface of aluminum and aluminum-lithium plate. Commercially-available alumina-fiber reinforced aluminum alloy tapes were used as the reinforcing material. Vacuum hot pressing was used to bond the reinforcing tape to aluminum alloy 2219 and aluminum-lithium alloy 2195 base plates. Static and cyclic three-point bend testing and metallurgical analysis were used to evaluate the enhancement of mechanical performance and the integrity of the bond between the tape and the base plate. The tests demonstrated an increase in specific bending stiffness. In addition, no issues with debonding of the reinforcing tape from the base plate during bend testing were observed. The increase in specific stiffness indicates that selectively-reinforced structures could be designed with the same performance capabilities as a conventional unreinforced structure but with lower mass.

Introduction

Selective reinforcement of high-stress regions of metallic airframe fuselage and wing structures offers the potential for increased structural efficiency. Previous analytical and experimental studies of selectively-reinforced aluminum specimens have shown great potential for improving structural performance as well as for enhancing toughness and fatigue crack growth behavior (ref. 1-3). In one study, 7075 aluminum alloy open-hole compression panels were reinforced in selected locations using alumina fibers embedded in a thin aluminum tape (ref. 1). The selectively-reinforced panel exhibited 23% - 68% improvement in specific buckling load depending on the reinforcement architecture and loading conditions. In another study, selective reinforcement of 7075 aluminum alloy compact tension specimens was shown to improve the toughness and fatigue crack growth behavior (ref. 2). The selectively-reinforced specimens in these studies were prepared by either soldering or adhesively bonding the reinforcing tape into grooves machined into the specimens.

In addition to aircraft structural applications, selective reinforcement can offer performance improvements of other types of structural components such as integrally-stiffened propellant tanks and space exploration pressurized vessels. For the past several years, NASA has been investigating processes for fabricating near-net-shape integrally-stiffened unitized metallic structural shapes such as barrels, domes, and cones. Some examples of these efforts are described in references 4-5. Adding a reinforcing material to the stiffeners can lead to more

efficient structural designs for these types of components. The manufacturing efficiency would be improved by developing a method to bond the reinforcing material to the structure in-situ during the near-net-shape fabrication process.

This paper describes research efforts to assess the feasibility of selectively reinforcing aluminum structural components with fiber-reinforced metallic tapes. Exploratory processing experiments were conducted using vacuum hot press techniques to directly embed a commercially-available reinforcing material into aluminum and aluminum-lithium alloy plates. The goal of these experiments was not process optimization but rather to determine typical pressures and temperatures needed to establish adequate bonding between the reinforcing material and the base material. The integrity of these bonds was evaluated using microstructural analysis and three-point bend testing. In addition, in-situ bonding methods that can incorporate the reinforcing materials into structures during near-net-shape fabrication processes were explored and are discussed.

Materials

Two different base plate materials were used for these processing experiments: aluminum alloy 2219-T851 plate with thickness of 0.25 inch and aluminum-lithium alloy 2195-T8 with thickness of 0.190 inch. Base plates with thickness ranging from 0.18 inch to 0.25 inch were machined from these plates.

The reinforcing material was MetPreg™ tape, a commercially-available fiber-reinforced aluminum material. This tape consisted of a commercially-pure aluminum (Al-1100) matrix reinforced with 50 volume percent continuous Nextel™ 610 alumina fibers. The tape thickness was nominally 0.018 inch and the width was either 0.375 inch or 0.48 inch. Detailed information about this fiber-reinforced aluminum tape can be found in references 6-9. In addition to this MetPreg™ tape, two more variants of the tape were examined. One variant had the same fiber volume fraction but used an aluminum alloy matrix with 2 weight percent copper (Al-2Cu) instead of Al-1100. This tape was 0.018-inch thick by 0.375-inch wide. The other variant used the Al-1100 matrix but the tape thickness was increased to 0.180 inch. This thicker tape had a nominal width of 0.45 inch.

Experimental Procedures

Selective Reinforcement Process

A 190-ton vacuum hot press with temperature capability of 2300°F was used to consolidate the selectively-reinforced panels. Base plates were machined to the desired dimensions. Base plate width was in the range of 1 inch to 3 inches. The length varied from 2.75 inches to 6 inches. Some of the base plates had a groove machined into the surface deep enough to accommodate the reinforcing tape. The base plates and reinforcing tapes were chemically cleaned prior to consolidation processing. The base plate and tape stacking sequence was assembled. In some cases, stainless steel dies were used to limit the outward flow of the base plate material during

hot pressing. Boron nitride anti-seize compound and molybdenum foils were used to protect the hot press platens and any dies that were used to support the assembly. The hot press chamber was evacuated and heated to the target processing temperature. The platens were engaged to apply the consolidation load to the assembly for the desired length of time. The platens were then disengaged to remove the load and the consolidated panel was allowed to furnace cool.

Static 3-Point Bend Tests

Three-point bend tests were conducted on specimens machined from some of the consolidated panels to evaluate the mechanical integrity of the bond between the base plate and the reinforcing tape. ASTM Standards D7264 and E85 (ref. 10 and 11) were used as guides for the tests. However, the specimen dimensions did not meet the dimensional requirements from the standards due to size limitations of the consolidated panels. The 3-point bend test apparatus is shown in figure 1. The base of the load fixture was attached to the load cell mounted to the test machine. Specimens were tested using a span of 3 inches. The mid-span load was applied to the specimen using the test machine's hydraulic ram at a constant deflection rate of 0.01 inch/minute. An extensometer was located beneath the specimen to measure deflection at the mid-span location. An automated data acquisition system collected the load and deflection data. Multiple tests were conducted on each specimen at low loads to evaluate the stability of the load-deflection behavior for the selectively-reinforced material. Testing was performed with the reinforced surface in either tension or compression (see figure 2). Bending stiffness was defined as the slope of the load-deflection curve and was calculated by linear regression. Eventually, the specimens were loaded to failure to investigate the fracture behavior of the selectively-reinforced material and the integrity of the bond line.

3-Point Bend Fatigue Tests

Following static 3-point bend testing at low loads, two of the specimens were selected for fatigue testing. Tests were conducted with a span of 3 inches using the apparatus shown in figure 1. The specimens were configured such that the reinforced surface was loaded in tension. An R ratio of 0.1 was used. The target frequency was 5 Hz.

The fatigue test load cycle sequence is illustrated in figure 3 . The initial maximum fatigue load was 50 lbs and the specimen was fatigued for 50,000 cycles. The test was paused and the maximum fatigue load was increased by 10 lbs. The specimen was then fatigued for another 50,000 cycles. The maximum fatigue load was incremented by 10 lbs following each set of 50,000 cycles until the specimen failed. In addition, static bend tests up to the maximum fatigue load were conducted before and after each set of fatigue cycles to determine if the load-deflection behavior was affected by fatigue cycling.

Microstructural Analysis

Microstructures and test specimen fracture surfaces were analyzed using optical and scanning electron microscopy.

Results and Discussion

Selectively-Reinforced Al-2219 Processing Experiments

Exploratory processing experiments were conducted to investigate selective reinforcement of thin Al-2219 plate. The panel components and processing parameters are summarized in table 1. The effects of the vacuum hot press parameters on the bond between the base plate and the reinforcing tape were evaluated with microstructural analysis.

Figure 4 shows a photograph of the components used for one of the selective reinforcement experiments. Figure 5 shows a diagram of the cross section of this panel assembly. A 0.48-inch wide by 0.03-inch deep groove was machined into the top surface of a 0.25-inch thick Al-2219 base plate. The MetPreg™ tape with the Al-1100 matrix was inserted in the groove. A 0.050-inch thick sheet of Al-2024 was positioned on top of the assembly to facilitate even distribution of the hot press load over the whole part. (Al-2024 sheet was used for this particular experiment because it was readily available in thin sheet form whereas the Al-2219 plate was thicker than desired for a thin cover plate.) The overall length and width of the panel assembly were 2.75 inches and 1.0 inch, respectively. The assembly was processed in the vacuum hot press at 930°F with a pressure of 15 ksi for 1 hour. Figure 6 shows a photograph of the consolidated panel (VHP-387) compared to a representative assembly. The processing temperature was very high and thus the materials exhibited a large degree of plastic flow. The hot-pressed panel had a thickness of 0.110 inch. The microstructure of the reinforced region is shown in figure 7. A good bond was formed between the reinforcing tape and both the Al-2219 base plate and the Al-2024 cover sheet, but the tape exhibited excessive lateral flow due to the applied pressure at high temperature. A second assembly was hot pressed for one hour at a slightly lower temperature (890°F) and a much lower pressure (0.35 ksi). This panel (VHP-388) did not have the extreme deformation that was observed in the previous panel. However, due to the low consolidation pressure, the tape did not adhere to the base plate.

Subsequent experiments to bond the tape to the Al-2219 surface involved applying the hot press load directly to the tape instead of distributing the load over the whole panel surface. Figure 8 shows a photograph of the panel assembly and a schematic of the cross section for this loading configuration. Two pieces of Al-2219 plate were used. A 0.48-inch wide by 0.04-inch deep groove was machined into the surface of the base plate. The top plate had the surface machined down such that a 0.48-inch wide by 0.06-inch tall stub was left on the surface that would fit into the groove on the base plate. The tape with the Al-1100 matrix was pre-placed in the groove and the stub of the top plate was inserted into the groove on top of the tape. The assembly had a gap between the top plate and base plate of approximately 0.04 inch. The overall length and width of the assembly were 6 inches by 2 inches, respectively. The length and width of the tape over which the hot press load was applied were 6 inches by 0.48 inch, respectively. This assembly was processed at 570°F for 15 minutes at a constant load such that the pressure applied to the surface of the tape was 60 ksi. Figure 9 shows a photograph of the consolidated panel (VHP-391). The materials in the vicinity of the reinforcing tape were well consolidated. A high consolidation pressure was maintained on the reinforcing tape because the gap between the two plates did not close up enough to cause significant load redistribution. The microstructure of the interface region (figure 10) shows some signs of cracking between the tape and the base plate.

Selectively-Reinforced Al-2195 Processing Experiments

Exploratory processing experiments were conducted to investigate selective reinforcement of thin Al-2195 aluminum-lithium alloy plate. The panel components and processing parameters are summarized in table 2. All of these experiments had the reinforcing tape pre-placed on the flat surface of the base plate such that the consolidation load was applied directly to the tape. The effect of the vacuum hot press parameters on the bond between the base plate and the reinforcing tape was evaluated with microscopy and 3-point bend testing.

Figure 11 shows a diagram of the assembly used to fabricate selectively-reinforced Al-2195 panels. Base plates with thickness of 0.185 inch were machined from a thicker plate of Al-2195-T8. The base plates were 2.5 inches long by 1 inch wide. No grooves were machined into the plates. A strip of the MetPreg^{TM} tape with either the Al-2Cu matrix or the Al-1100 matrix was pre-placed onto the surface. The tape width and thickness was 0.375 inch by 0.018 inch. Plates were processed in the vacuum hot press using the parameters shown in table 2. The processing temperatures were significantly higher than those for which the Al-2219 panels exhibited a good bond with the reinforcement. These higher temperatures were selected to allow plastic deformation in the base plate material such that the tape could be embedded into the plate.

Figure 12 shows photographs of the consolidated panels as well as the microstructure of the interface between the tape and the base plate. The base plate material deformed enough to allow the tape to become embedded into the base plate such that the top surface of the tape was flush with the top surface of the plate. The consolidation pressure decreased after enough deformation occurred to allow the top platen to come into contact with the top surface of the base plate. The microstructures show that the panels were well consolidated with no apparent cracks or defects at the bond lines.

Based on these successful bonding experiments, several more panels were fabricated for 3-point bend testing. Figure 13 shows the configuration used for panel fabrication. Panels were fabricated with either one strip or a stack of two strips of tape pre-placed onto the surface of the Al-2195 base plates. The two strips of wider tape were used to increase the volume fraction of selective reinforcement in the panel. The base plates were nominally 5 inches long by 1 inch wide by 0.17 inch thick (see table 2). Figure 14 shows the panel assembly with one strip of tape in the hot press chamber. Four panels with the Al-2Cu matrix were processed simultaneously at 800°F and 11 ksi (with respect to the tape surface) for 5 minutes (VHP-412-1, -2, -3, and -4). In addition, four panels with a stack of two strips of tape with Al-1100 matrix were processed simultaneously in a second hot press run using the same parameters (VHP-423-1, -2, -3, and -4).

Seven of the eight panels appeared to be well bonded. One panel with one strip of tape (VHP-412-4) did not exhibit good bonding between the tape and the base plate. The tape fell off after removal of the panel from the hot press. It is likely that the platens did not exert the full force on this specimen and thus the tape did not experience the required bonding pressure. This specimen was used to measure the mass increase associated with adding reinforcing tape to the base plate. The mass of the components of this panel was measured following the tape delamination. The base plate mass was 30.8439 grams while the tape mass was 1.1506 grams. Thus, the single

layer of tape increased the mass of the base plate by approximately 4%. This measurement can be used to calculate specific mechanical properties of selectively-reinforced specimens on a mass-normalized basis.

Figure 15 shows representative microstructures for panels fabricated with one and two layers of tape. In all cases, the reinforcing tapes were embedded into the base plate such that the top surface of the tape was flush with the top surface of the base plate. The specimen with two layers of tape (VHP-423-1) showed a pronounced bond line between the two pieces of tape. The higher-magnification view shows porosity along the bond line between the two tape layers, which was typical for the specimens produced with two layers of tape. The cause of the porosity has not yet been determined.

With the exception of the panel in which the tape was not bonded, all of the panels exhibited significant distortion due to thermal expansion mismatch between the tape and base plate (see figure 16). The coefficient of thermal expansion (CTE) for Al-2195 alloy is approximately 14 μin/in/°F (ref. 12) over the processing temperature range. The MetPreg™ tape has a significantly lower CTE of 4 μin/in/°F (ref. 6). During cool-down from the processing temperature, the tape and base plate constrain each other such that the resultant consolidated panel has the tape in a state of residual compression and the base plate in residual tension.

Selectively-Reinforced Al-2195 Bend Testing

Static 3-point Bend Tests

Each of the eight Al-2195 panels selectively-reinforced with one and two strips of tape was machined to produce 3-point bend specimens. The ends of the panels were trimmed off to be used for microstructural analysis and the edges were machined to produce specimens that were 4 inches long by 1 inch wide with the embedded tape centered on the top surface of the base plate (see figure 17). Following low-load bend testing, some of the specimens had the edges machined down such that there was no excess base plate on the sides of the specimen (see figure 18). The de-bonded specimen (VHP-412-4) was used as a baseline to evaluate the bending behavior of the unreinforced base plate. This specimen had a shallow groove in the top surface where the tape had been placed.

Figure 19 shows 3-point bend load-deflection curves from the first three tests on specimen VHP-412-3 with one layer of reinforcing tape. The specimen was configured such that the reinforced side of the specimen was loaded in compression. The specimen was loaded to 100 lbs and unloaded back to zero during the three separate tests. The bending behavior was very stable with no hysteresis. The same load-deflection curve was generated during loading and unloading for each test. The bending stiffness was approximately 9400 lb/in.

The specimen was also tested three times with the reinforced side loaded in tension. Figure 20 shows the results. The loading portion of the load-deflection curve for the first test exhibited a large degree of non-linearity while the curve was linear during unloading. The second and third tests generated linear load-deflection curves during loading and unloading. The bending stiffness calculated from these curves was approximately 9000 lb/in. The nonlinearity during the

first loading was most likely a result of base plate yielding due to residual stresses near the interface between the tape and the base plate. The Al-2195 alloy yielded at a relatively low load as the bending load superimposed additional tensile stress onto the residual tensile stress in the base plate. During subsequent tests, the specimen accommodated the 100-lb bending load without yielding due to the work hardening from the first cycle. In the initial set of tests in which the specimen was loaded such that the reinforced side was placed in compression, the load-deflection curve was linear because the residual tensile stress in the base plate allowed it to accommodate higher applied compressive stresses from the bending load without yielding. The specimens reinforced with two strips of tape had similar results.

Figure 21 shows a comparison of the bending stiffness of specimens with one and two layers of tape reinforcement. Also shown are stiffness data for the specimen without tape reinforcement (VHP-412-4). This is the specimen from which the tape failed to bond to the base plate during vacuum hot pressing. All of the specimens had nominal width and thickness dimensions of 1.00 inch and 0.17 inch, respectively, and were tested with a 3-inch span. Each data point represents one test. The unreinforced specimen had an average bending stiffness of 8370 lb/in over 6 tests with a tight scatter band. The standard deviation (SD) was 43 lb/in. The three specimens with one layer of reinforcing tape had much greater variability in the stiffness measured from test-to-test as well as from specimen-to-specimen. Two of these specimens (VHP-412-1 and 2) had average bending stiffness values of 8490 lb/in (SD = 409 lb/in) and 8360 lb/in (SD = 160 lb/in), respectively, which were similar to the stiffness of the unreinforced specimen. Specimen VHP-412-3 had an average bending stiffness of 9410 lb/in (SD = 256 lb/in). For this particular specimen, increasing the mass by 4% by adding reinforcing tape resulted in a 12% increase in bending stiffness. Thus, selective reinforcement increased the specific stiffness of the Al-2195 base plate. The specimen with two layers of tape (VHP-423-1) had results similar to those for specimen VHP-412-3 with only one layer of tape. It had a bending stiffness of 9230 lb/in (SD = 303 lb/in). Although all of the specimens had the same nominal cross-section dimensions, part of the specimen-to-specimen variation can be attributed to small differences between the measured specimen thickness. The bending stiffness is proportional to the specimen thickness raised to the 3rd power. Thus, small thickness differences can result in significant stiffness differences.

Following multiple low-load bending tests to assess stiffness behavior, two of the specimens with one layer of tape reinforcement were tested to failure. Figure 22 shows the load-deflection curve and post-test photographs of specimen VHP-412-1. This specimen was loaded such that the reinforced side was in tension. The specimen exhibited tensile fracture of the reinforcing tape at a load of 225 lbs. This fracture compromised the load-carrying capability of the specimen and the load decreased rapidly to about 180 lbs. At this point, the base plate was able to carry the load and the load began increasing again. Eventually the test was stopped without further fracture and the specimen was unloaded.

Figure 23 shows the load-deflection curve and post-test photographs of specimen VHP-412-3, which was tested such that the reinforced side was in compression. The specimen exhibited buckling of the tape at 440 lbs. This tape buckling compromised the load-carrying capability of the specimen and the load decreased rapidly to about 300 lbs. At this point, the base plate was able to carry the load and the load began increasing again. Eventually the test was stopped without further fracture and the specimen was unloaded.

In addition, two of the specimens with two layers of tape reinforcement were tested to failure. These specimens had the same failure modes as did the specimens with one layer of tape reinforcement. The specimen loaded with the reinforced side in tension exhibited tensile failure of the tape while the specimen loaded with the reinforced side compression exhibited localized buckling of the tape. Neither specimen showed signs of delamination at the base plate-to-tape interface or the tape-to-tape interface.

3-point Bend Fatigue Tests

Specimen VHP-412-2 with one layer of reinforcing tape and specimen VHP-423-2 with two layers of reinforcing tape were selected for fatigue testing. The edges of the specimens were trimmed off to remove the excess Al-2195 base plate in order to have the bond line between the base plate and reinforcing tape exposed along the entire length of the specimen. Figure 24 shows a cross-section photograph of the specimens. Once the specimens were modified, they were renamed VHP-412-2-MOD and VHP-423-2-MOD. The final width of the two specimens was 0.40 inch and 0.35 inch, respectively. The specimens were tested such that the reinforced side was loaded in tension. Several static 3-point bend tests were conducted on the specimens to a maximum load of 50 lbs to establish baseline load-deflection curves prior to fatigue testing.

Figures 25 and 26 show the load-deflection curves for the two specimens before and after 50,000 fatigue cycles at a maximum fatigue load of 50 lbs. No change in bending behavior was observed due to fatigue. This result was typical for each of the sets of 50,000 fatigue cycles at the incrementally-increased maximum fatigue loads. Table 3 shows the bending stiffness for both specimens measured before and after each set of fatigue cycles. The bending stiffness after each set of fatigue cycles was within 5% of that measured prior to fatigue testing.

Specimen VHP-412-2-MOD with one layer of tape was subjected to 5 sets of 50,000 fatigue cycles at maximum fatigue loads of 50 lbs to 90 lbs in increments of 10 lbs without failure or changes in load-deflection behavior. The specimen was inadvertently overloaded during test setup for the 100-lb maximum fatigue load test. The tape fractured in tension but remained bonded to the Al-2195 base plate (see figure 27).

Specimen VHP-423-2-MOD with two layers of tape was subjected to 8 sets of 50,000 fatigue cycles at maximum fatigue loads of 50 lbs to 120 lbs in increments of 10 lbs without failure or changes in load-deflection behavior. During fatigue testing at a maximum load of 130 lbs, the specimen failed after approximately 13,000 cycles. Figure 28 shows a photograph of the overall view of the failed specimen and an scanning electron micrograph of the fracture region. The outer layer of tape delaminated from the inner layer of tape. This loss of load-carrying capability resulted in overload of the specimen and tensile fracture of the inner tape. The inner tape remained bonded to the base plate.

Selective Reinforcement of Al-2195 Stiffeners

An experiment was conducted to simulate the in-situ selective-reinforcement of Al-2195 during near-net-shape processing of integrally-stiffened structure. A stainless steel die was fabricated

with a channel that was 0.45 inch wide, and 0.5 inch deep. A 0.180-inch thick strip of custom-fabricated MetPreg^{TM} tape was positioned in the bottom of the channel. A 0.7-inch tall block of Al-2195 was placed in the die and hot pressed at 800°F and 10 ksi pressure for 5 minutes (VHP-444).

Figure 29 shows a photograph of the specimen/die assembly prior to hot press consolidation. The specimen was wrapped in molybdenum foil to protect the die and platens. The consolidated specimen is shown in figure 30. The reinforcing tape appeared to be well bonded to the top of the simulated stiffener. The stiffener is bowed due to residual stress. Microstructural analysis (figure 31) indicated a defect-free bond between the tape and the base plate. There were no signs of delamination. This experiment showed that bonding the tape directly to the face of the stiffener during the stiffener forming process is feasible.

Concluding Remarks

Exploratory processing experiments successfully demonstrated the feasibility of selectively reinforcing aluminum and aluminum-lithium based materials with continuous fiber-reinforced metallic tapes. These commercially-available reinforcing tapes, which consisted of 50 volume percent alumina fibers in an aluminum matrix, were bonded to Al-2219 and Al-2195 base plates. Vacuum hot press processing techniques were used to reinforce these base plates with the reinforcing tape. These techniques were not optimized but did show the feasibility of selective reinforcement.

Processing experiments were conducted in which the consolidation load was applied directly to the reinforcing tape as well as being distributed over the entire surface of the base plate. Application of the consolidation load directly to the tape embedded the tape into the base plate, formed good bonding between the tape and base plate, and limited the extent of lateral flow of the tape.

Static three-point bend tests and three-point bend fatigue tests were used to assess the mechanical performance of the selectively-reinforced Al-2195 materials and to evaluate the integrity of the bond between the reinforcement and the base plates. The bond between the reinforcing tape and the Al-2195 base plate performed very well. No debonding occurred during multiple low-load bending tests. In addition, bend tests were conducted to failure in which the reinforced side of the specimen was loaded in tension and in compression. At the failure load, the reinforcing tape failed in tension or buckled in compression, but the tape remained bonded to the base plate. In addition, the base plate was able to continue carrying load following failure of the reinforcing tape.

Selectively-reinforced Al-2195 plate specimens showed improvements in performance. Although embedding a layer of reinforcing tape into the surface of the plate added 4% more mass, the bending stiffness was increased by 12%. This increase in specific stiffness indicated that selectively-reinforced structures could be designed with the same performance capabilities as a conventional unreinforced structure but with significantly lower mass.

A vacuum hot press processing experiment was also conducted that successfully simulated the in-situ bonding of reinforcing tape to the top surface of a stiffener. This demonstration suggests that incorporating selective reinforcement into stiffened structures during near-net shape fabrication processes is feasible.

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Tables

Table 1. Vacuum hot press processing parameters for selectively-reinforced Al-2219 panels.

Vacuum Hot Press Run No.	Tape Matrix	Tape Dimensions		Base Plate Dimensions			Temp.	Load	Pressure (tape)	Pressure (base plate)	Time	Comments
		width	thick.	length	width	thick.						
		in.	in.	in.	in.	in.	°F	tons	ksi	ksi	min.	
VHP-387	Al-1100	0.48	0.018	2.75	1.0	0.25	930	20.6	---	15.0	60	Al-2024 cover plate
VHP-388	Al-1100	0.48	0.018	2.75	1.0	0.25	890	0.5	---	0.35	60	Al-2024 cover plate
VHP-391	Al-1100	0.48	0.018	6.0	2.0	0.25	570	90.0	60.0	---	15	Load applied directly to tape surface

Table 2. Vacuum hot press processing parameters for selectively-reinforced Al-2195 panels.

Vacuum Hot Press Run No.	Tape Matrix	Tape Dimensions		Base Plate Dimensions			Temp.	Load	Pressure (tape)	Pressure (base plate)	Time	Comments
		width	thick.	length	width	thick.						
		in.	in.	in.	in.	in.	°F	tons	ksi	ksi	min.	
VHP-398	Al-1100	0.375	0.018	2.5	1.0	0.185	730	22.0	46.9	17.6	5	
VHP-399	Al-2Cu	0.375	0.018	2.5	1.0	0.185	710	5.2	11.1	4.2	5	
VHP-412	Al-2Cu	0.375	0.018	5.0	1.0	0.170	800	40.0	10.7	4.0	5	Four panels fabricated simultaneously
VHP-423	Al-1100	0.48	0.018	4.6	1.0	0.170	800	47.9	10.8	5.2	5	Four panels fabricated simultaneously

Table 3. Three-point bending fatigue test parameters and stiffness data following sets of 50,000 fatigue cycles at incrementally increasing maximum fatigue loads for selectively-reinforced Al-2195 specimens.

Fatigue Set	**Fatigue Conditions**	**Cumulative No. of Fatigue Cycles**	**Post-Fatigue Bending Stiffness (lb/in)**	
			VHP-412-2-MOD (one layer of tape)	VHP-423-2-MOD (two layers of tape)
-------	prior to fatigue testing	0	4,010	4,827
1	50,000 cycles at P_{max} = 50 lbs	50,000	3,987	4,783
2	50,000 cycles at P_{max} = 60 lbs	100,000	4,085	4,830
3	50,000 cycles at P_{max} = 70 lbs	150,000	4,048	4,927
4	50,000 cycles at P_{max} = 80 lbs	200,000	4,031	4,784
5	50,000 cycles at P_{max} = 90 lbs	250,000	4,068	5,037
6	50,000 cycles at P_{max} = 100 lbs	300,000	-------	4,952
7	50,000 cycles at P_{max} = 110 lbs	350,000	-------	4,933
8	50,000 cycles at P_{max} = 120 lbs	400,000	-------	4,996

Figures

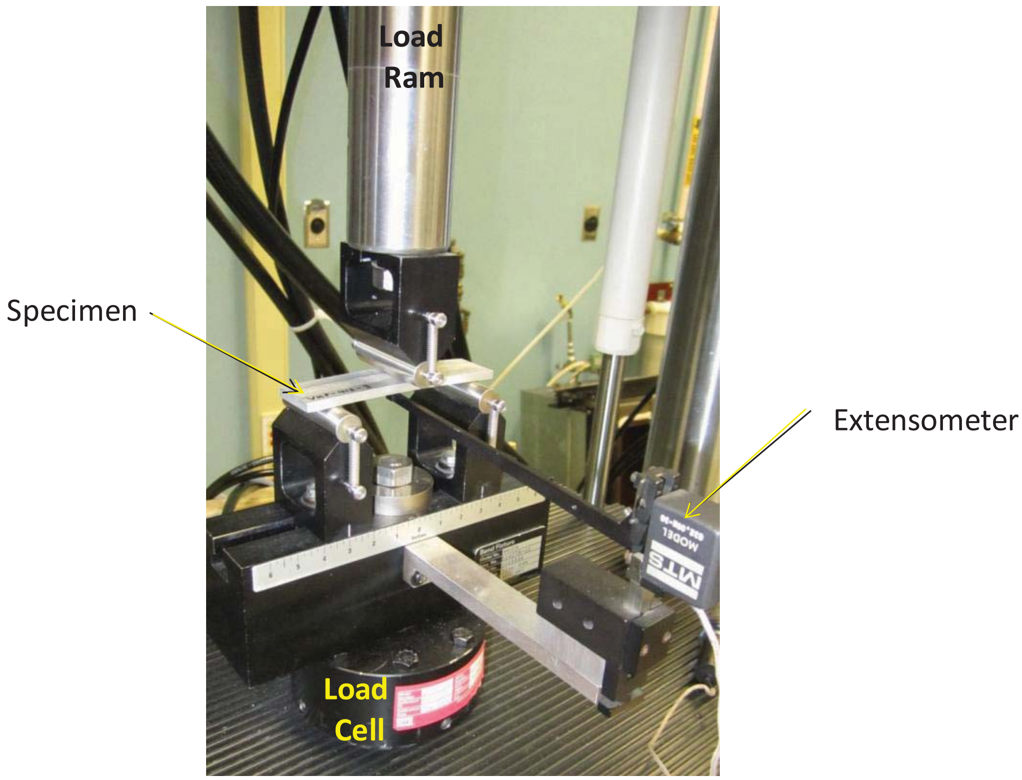

Figure 1. Photograph of three-point bend test apparatus.

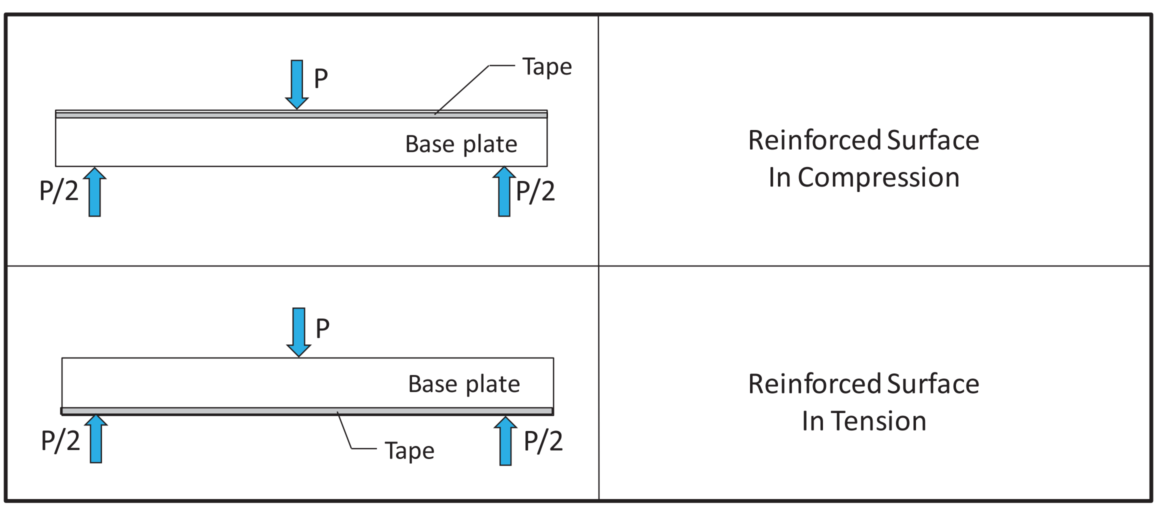

Figure 2. Three-point bend test specimen loading configurations.

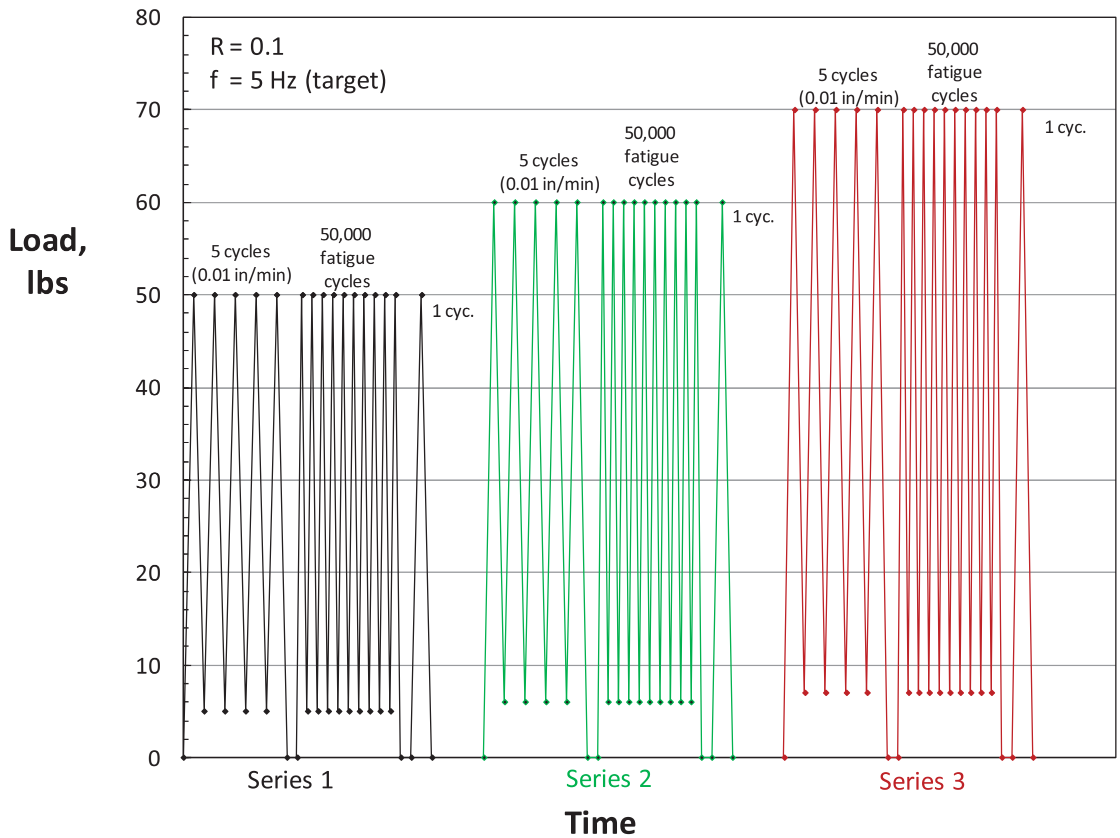

Figure 3. Three-point bend fatigue load cycle sequence.

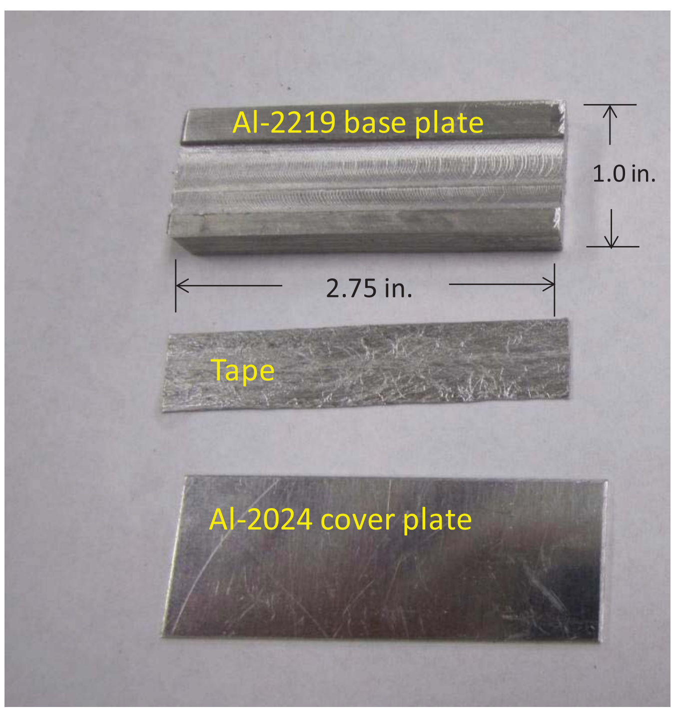

Figure 4. Photograph of panel components for selective reinforcement of Al-2219 plate.

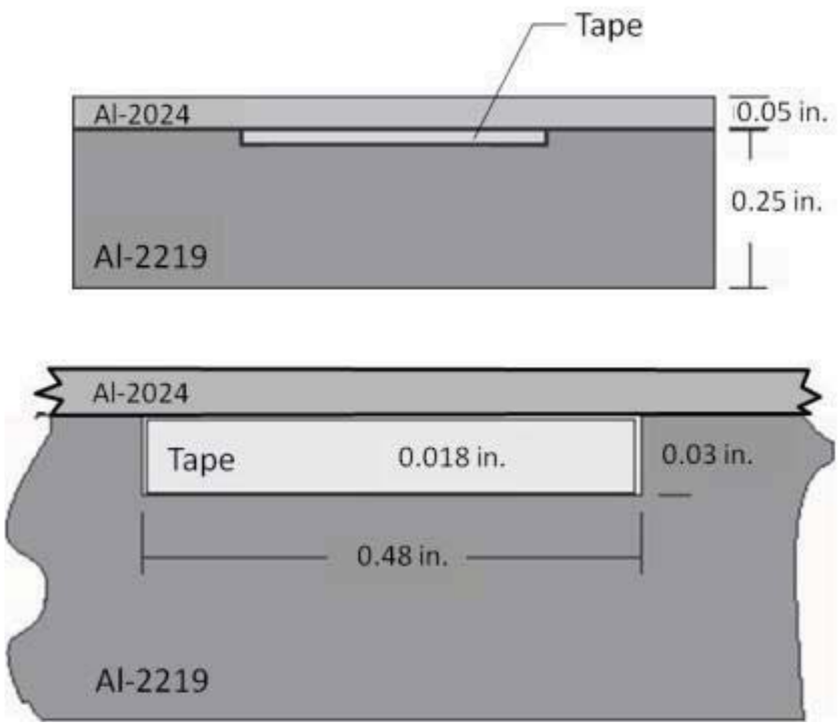

Figure 5. Diagram of panel configuration for selective reinforcement of Al-2219 plate.

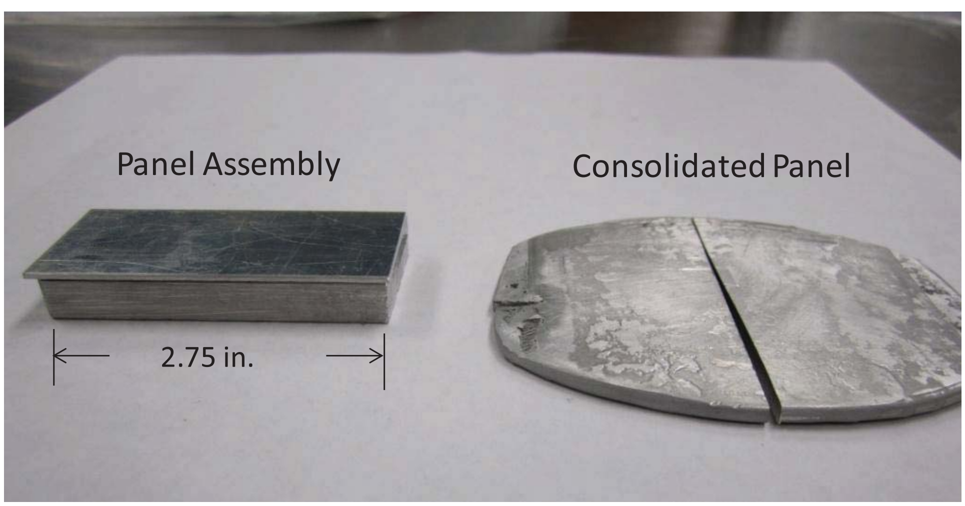

Figure 6. Photographs of representative panel assembly and selectively-reinforced Al-2219 panel (VHP-387) after consolidation at 930°F and 15 ksi for 1 hour.

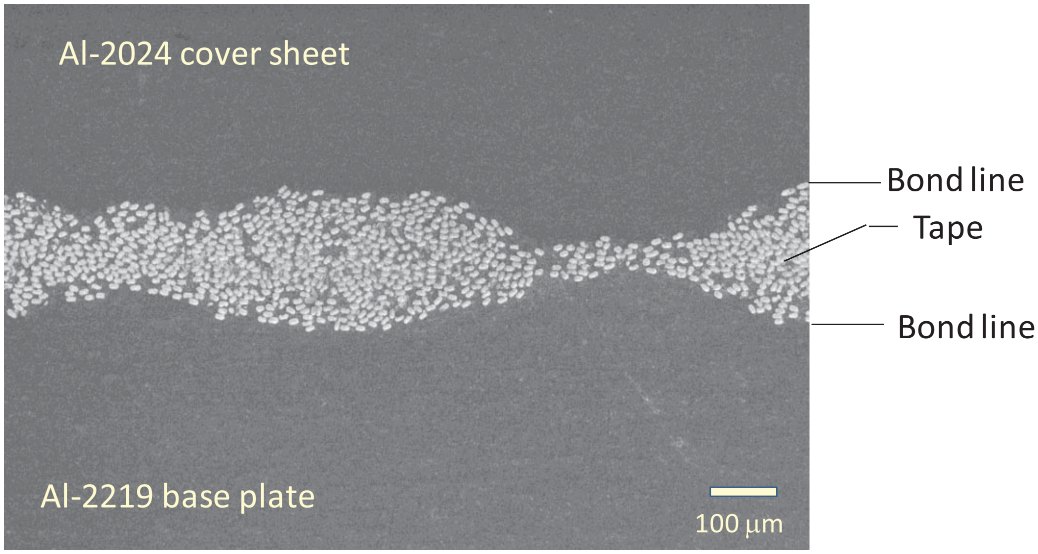

Figure 7. Photomicrograph of selectively-reinforced Al-2219 panel (VHP-387).

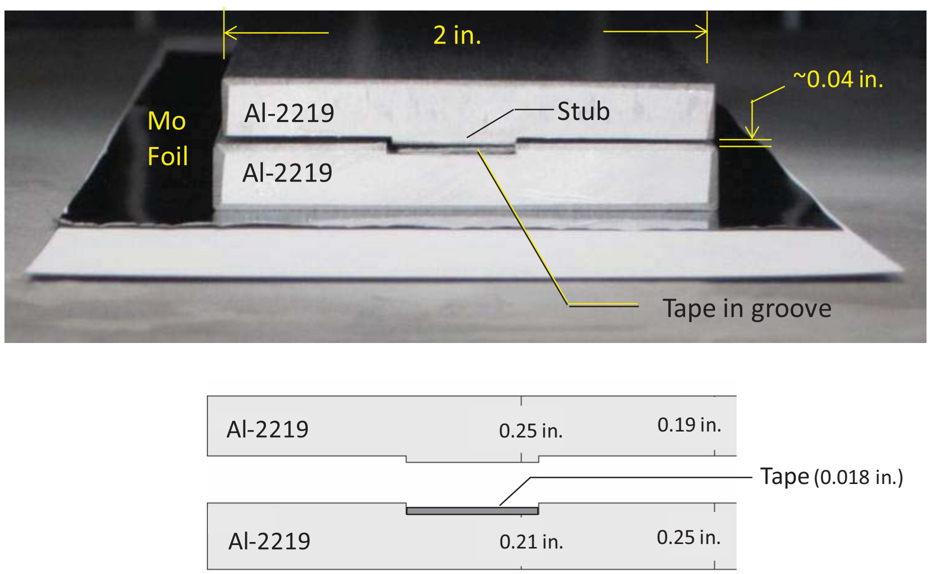

Figure 8. Photograph and diagram of Al-2219 panel configuration with stub for applying consolidation load directly to reinforcing tape (VHP-391).

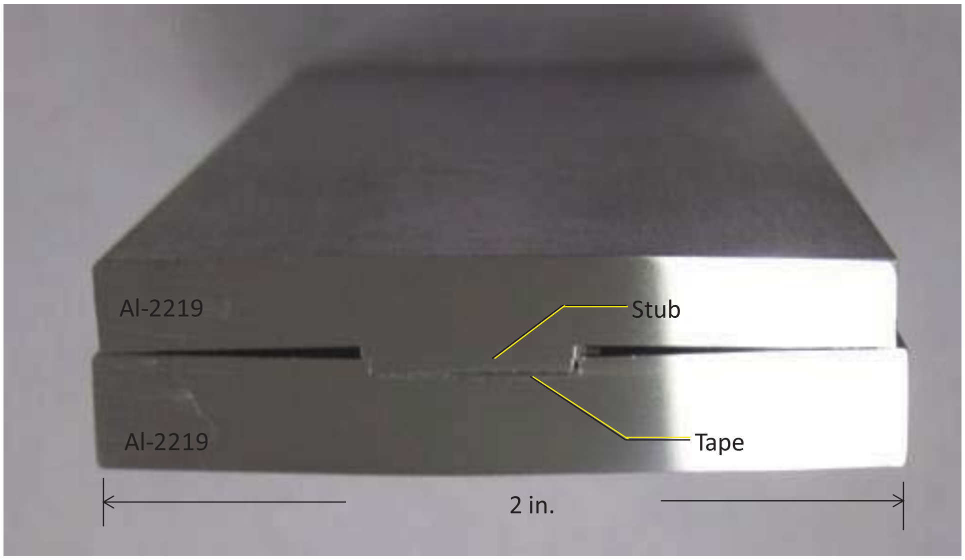

Figure 9. Photograph of Al-2219 panel (VHP-391) consolidated at 570°F and 60 ksi for 15 minutes with load applied directly to reinforcing tape.

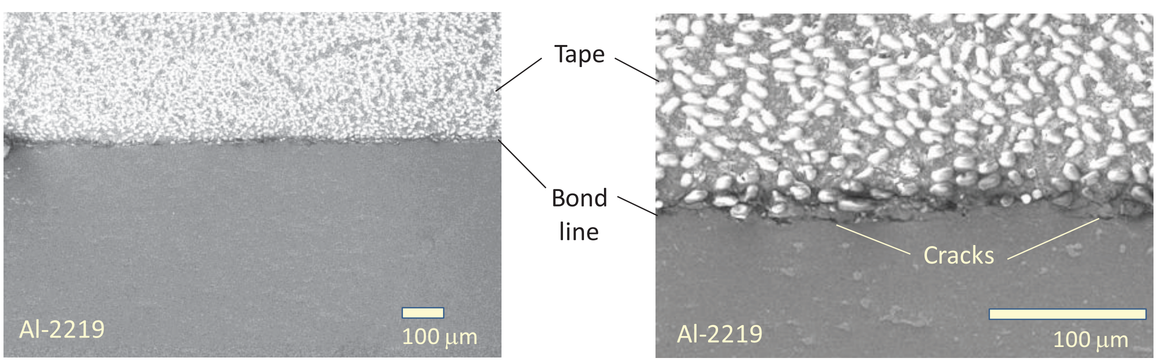

Figure 10. Photomicrographs of Al-2219 panel (VHP-391) with selective reinforcement.

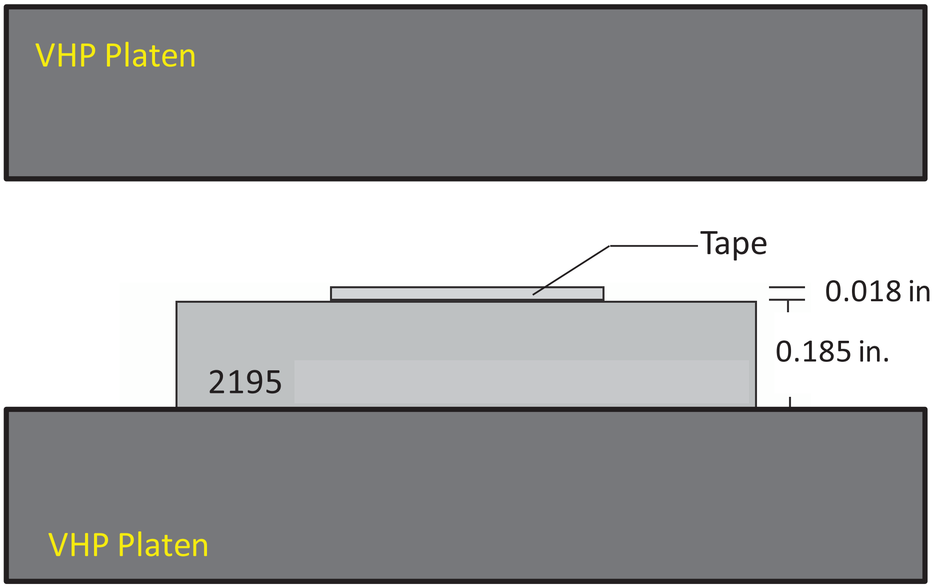

Figure 11. Diagram of panel assembly used to evaluate selective reinforcement of Al-2195.

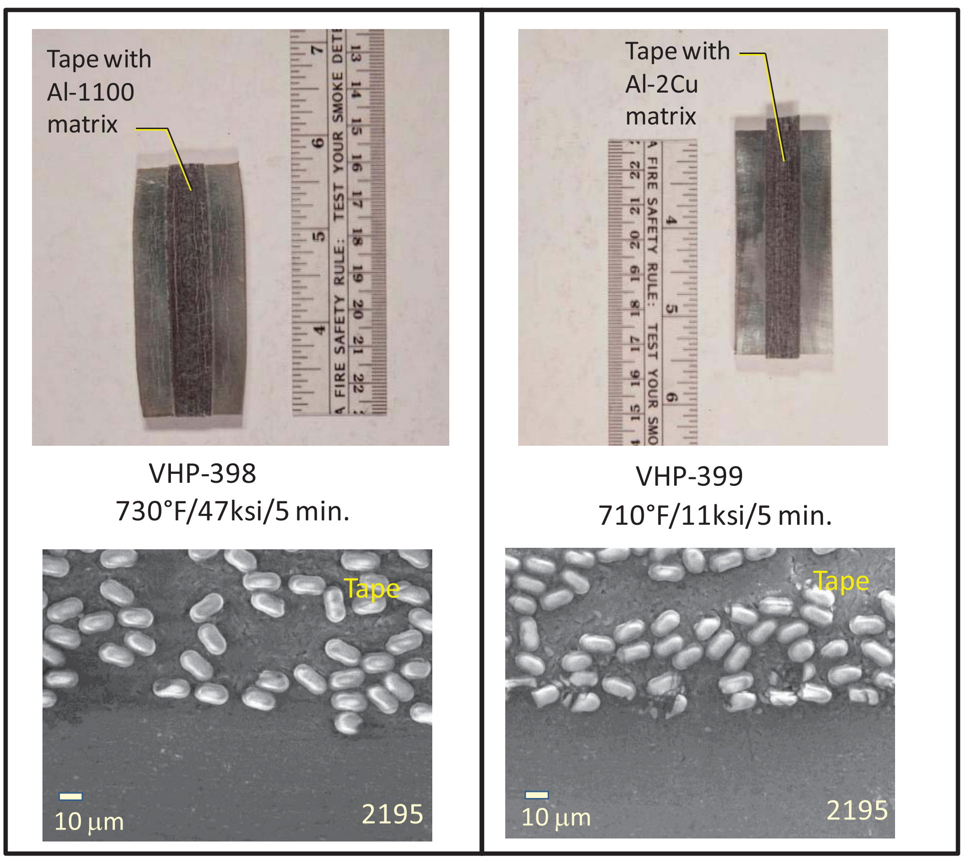

Figure 12. Photographs of consolidated selectively-reinforced Al-2195 panels and microstructures of the tape/base plate interface.

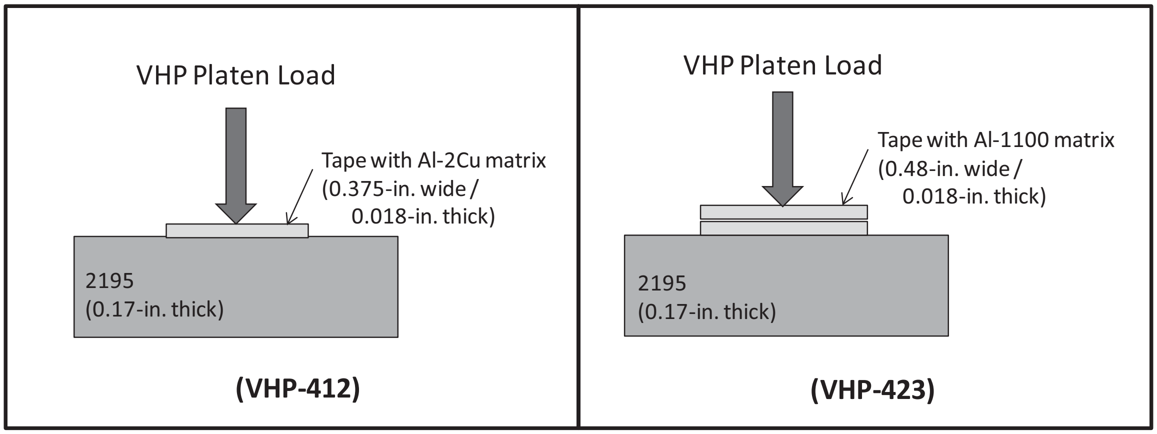

Figure 13. Diagram of assemblies for fabricating selectively-reinforced Al-2195 panels with one and two tape layers for bend testing.

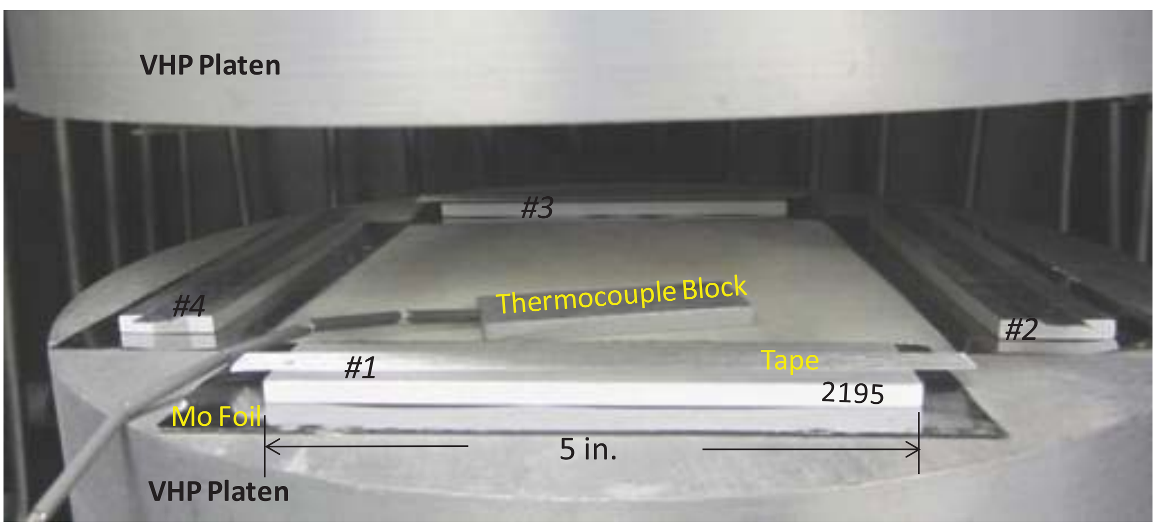

Figure 14. Photograph of vacuum hot press set-up for simultaneously consolidating four selectively-reinforced Al-2195 panels with one layer of tape (VHP-412).

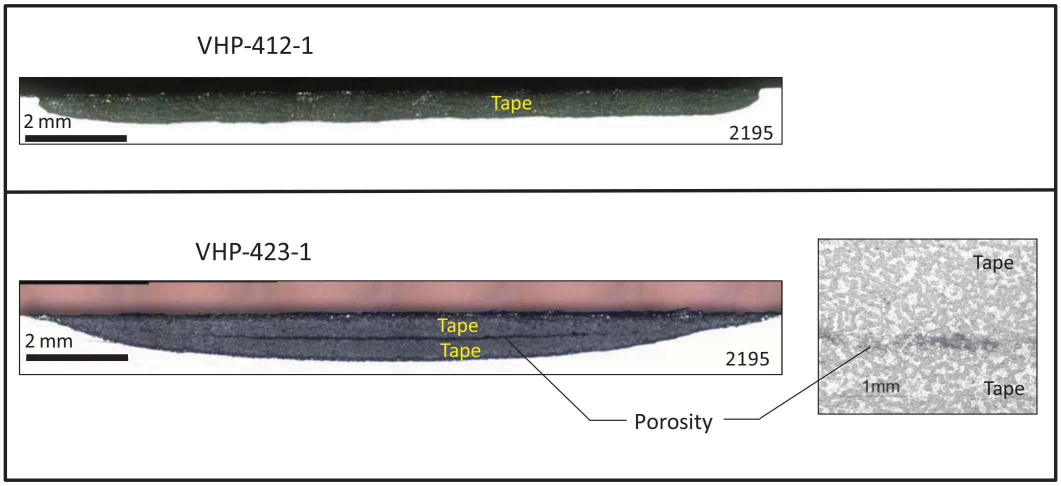

Figure 15. Photomicrographs showing representative microstructures of Al-2195 panels selectively-reinforced with one layer (VHP-412-1) and two layers (VHP-423-1) of tape.

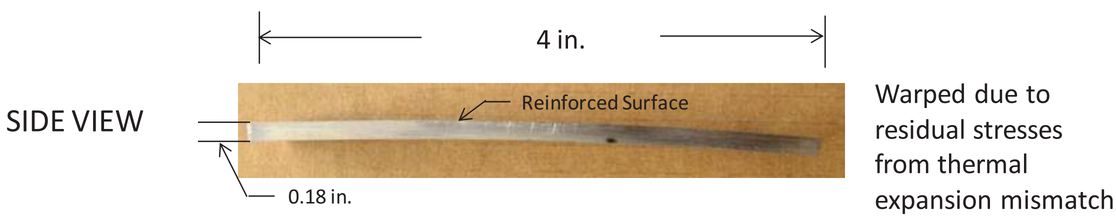

Figure 16. Side view photograph of selectively-reinforced Al-2195 panel showing distortion due to thermal expansion mismatch between tape and base plate.

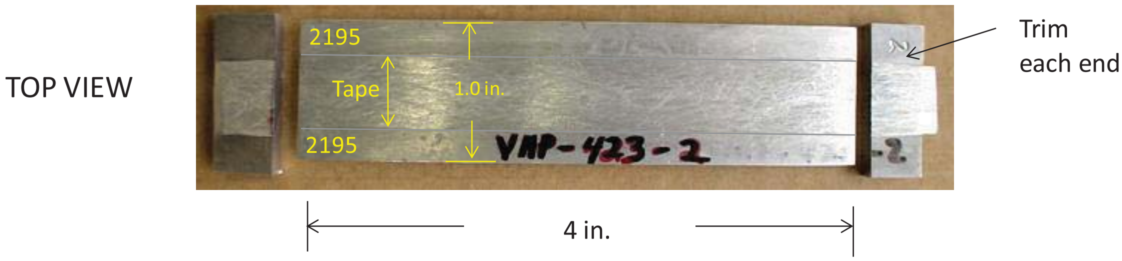

Figure 17. Top view photograph of three-point bend specimen machined from selectively-reinforced Al-2195 panel.

Figure 18. Top view photograph of selectively-reinforced Al-2195 three-point bend specimen with excess Al-2195 base plate edges trimmed off.

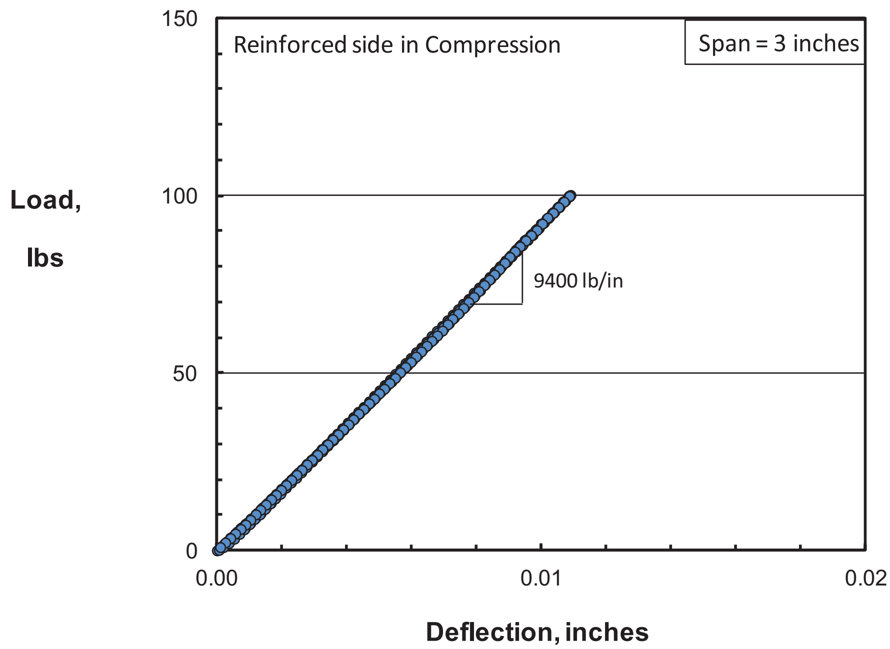

Figure 19. Three-point bend load-deflection curves for Al-2195 specimen VHP-412-3 with one layer of reinforcing tape loaded and unloaded three separate times (reinforced side loaded in compression).

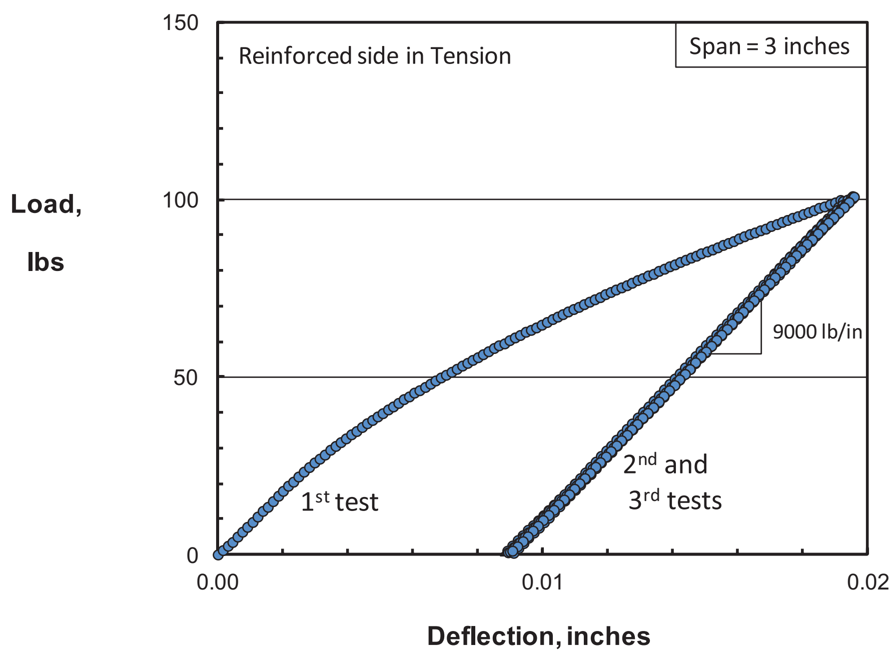

Figure 20. Three-point bend load-deflection curves for Al-2195 specimen VHP-412-3 with one layer of reinforcing tape loaded and unloaded three separate times (reinforced side loaded in tension).

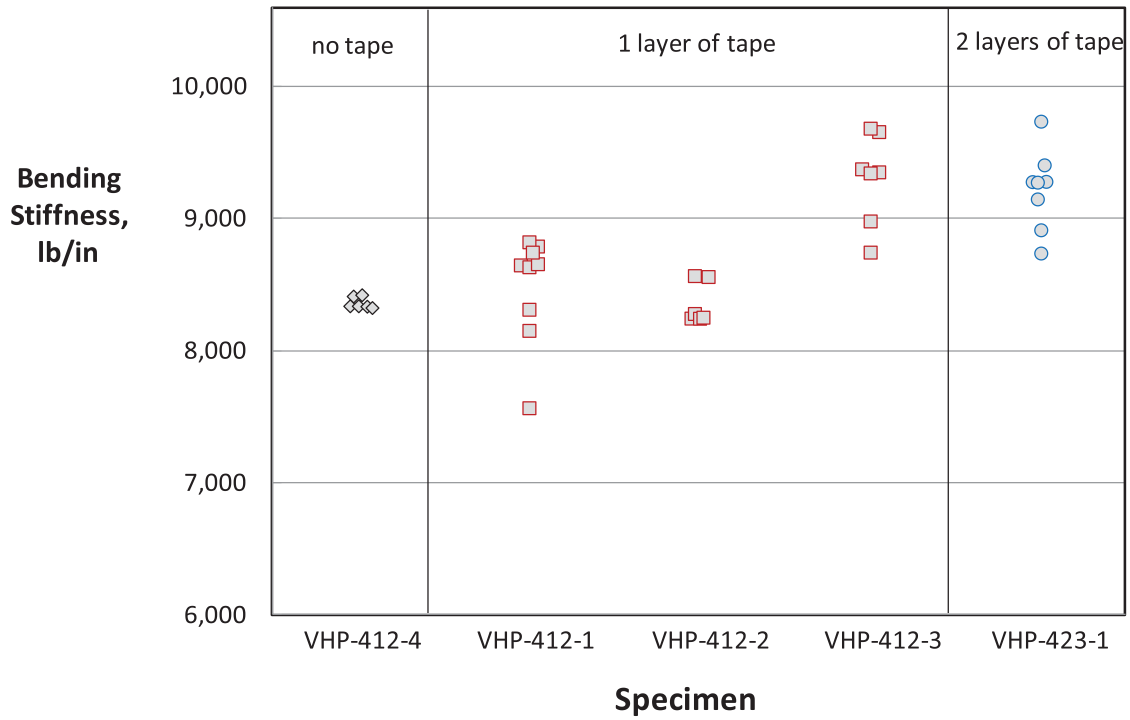

Figure 21. Bending stiffness measured from selectively-reinforced Al-2195 specimens. (Each data point represents one 3-point bending test.)

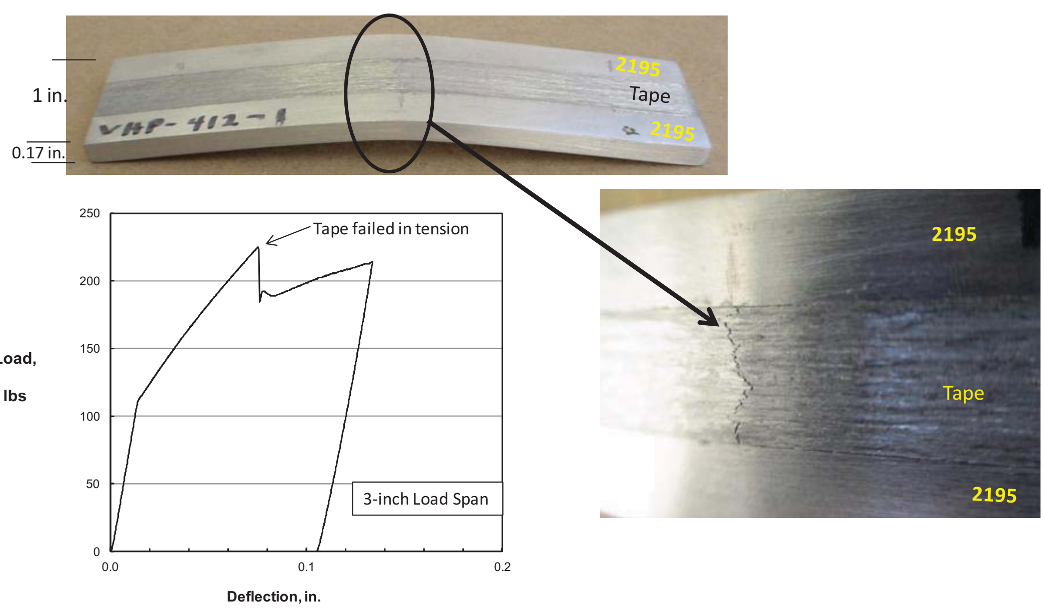

Figure 22. Three-point bend load-deflection curve and photographs of failure mode for selectively-reinforced Al-2195 specimen VHP-412-1 with one layer of tape loaded to failure. (Tape side loaded in tension.)

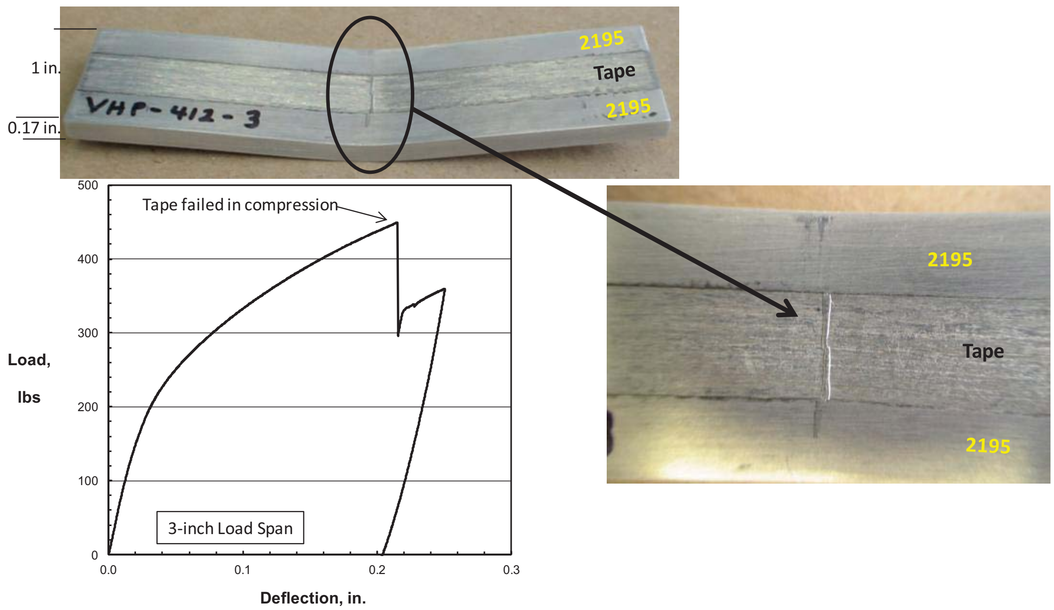

Figure 23. Three-point bend load-deflection curve and photographs of failure mode for selectively-reinforced Al-2195 specimen VHP-412-3 with one layer of tape loaded to failure. (Tape side loaded in compression.)

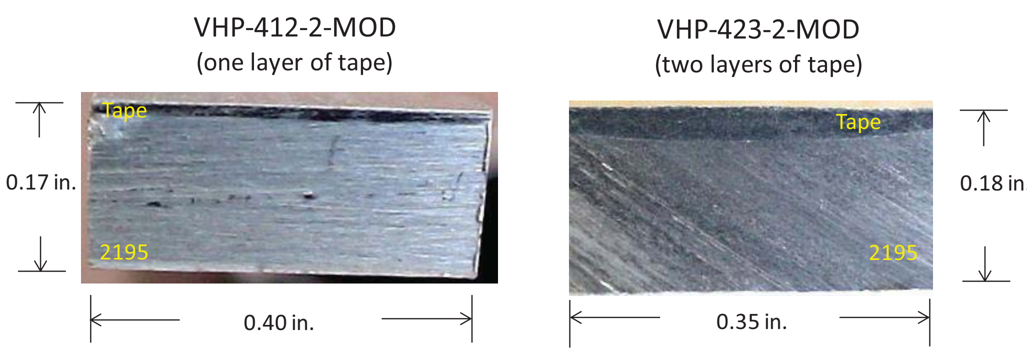

Figure 24. Photographs of cross sections of Al-2195 three-point bend fatigue specimens selectively reinforced with one and two layers of tape.

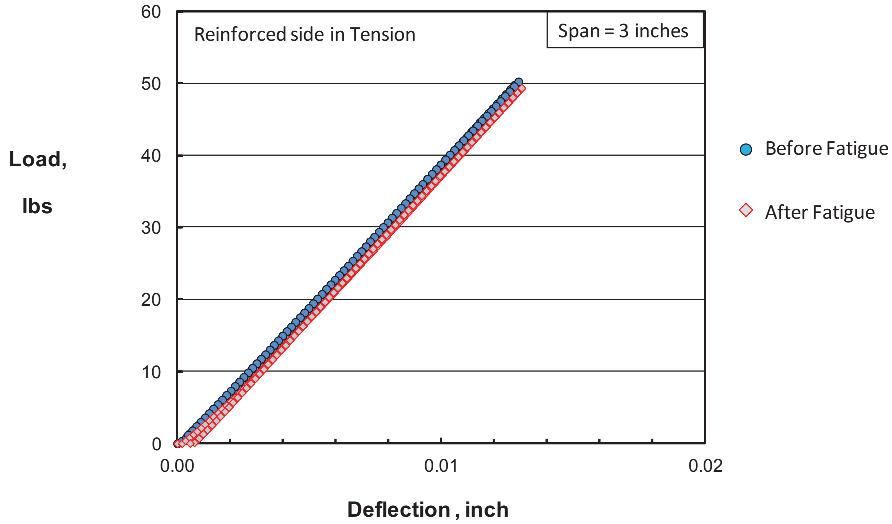

Figure 25. Three-point bend load-deflection curves for Al-2195 specimen VHP-412-2-MOD selectively reinforced with one layer of tape before and after 50,000 fatigue cycles with a maximum fatigue load of 50 lbs. (Reinforced side loaded in tension.)

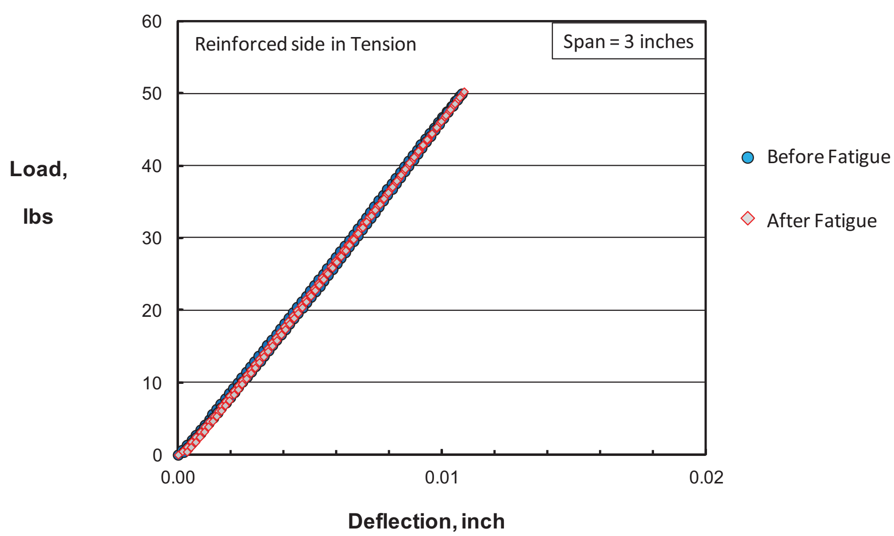

Figure 26. Three-point bend load-deflection curves for Al-2195 specimen VHP-423-2-MOD selectively reinforced with two layers of tape before and after 50,000 fatigue cycles with a maximum fatigue load of 50 lbs. (Reinforced side loaded in tension.)

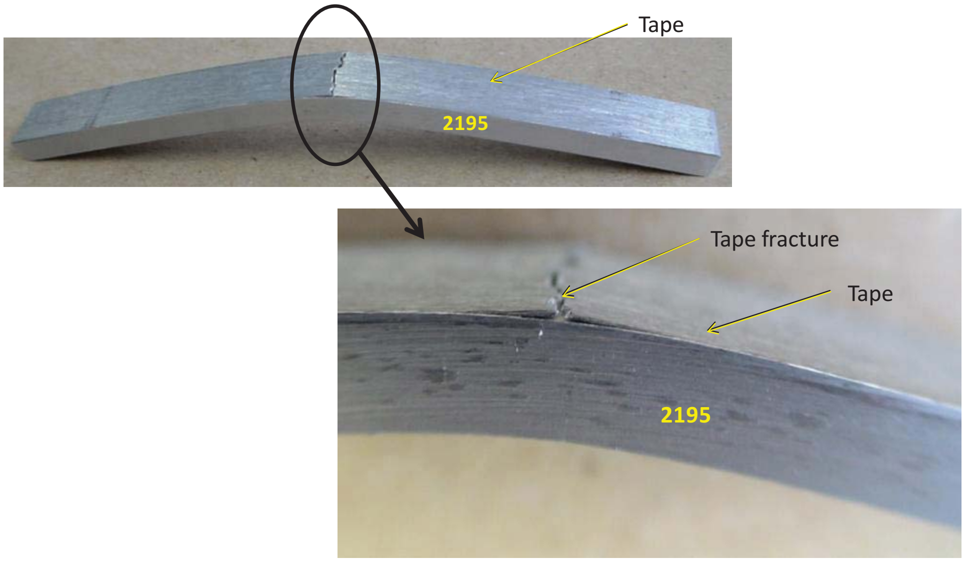

Figure 27. Photograph showing failure mode of Al-2195 specimen VHP-412-2-MOD selectively reinforced with one layer of tape inadvertently loaded to failure between sets of fatigue cycles. (Reinforced side loaded in tension).

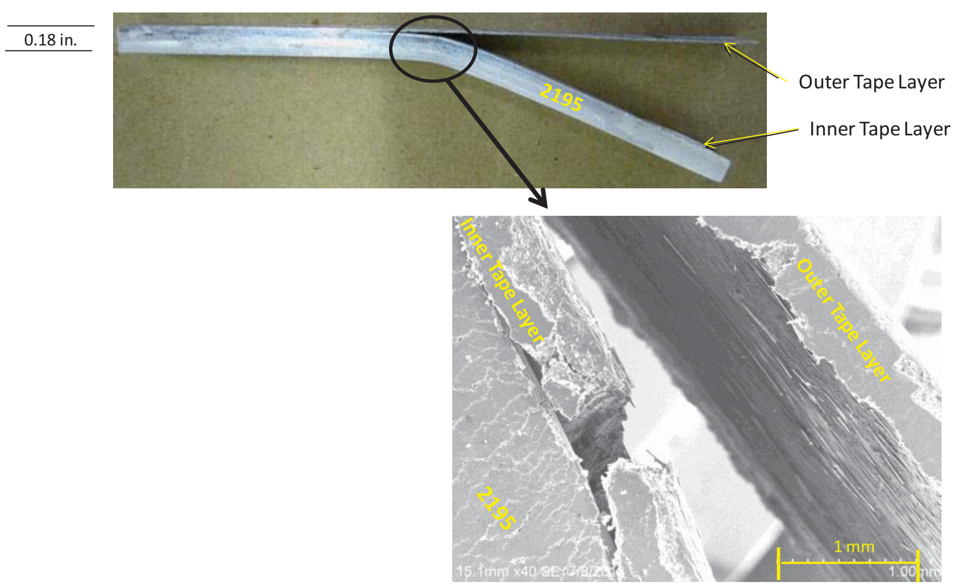

Figure 28. Photograph and electron photomicrograph showing failure mode of Al-2195 specimen VHP-423-2-MOD selectively reinforced with two layers of tape that failed during fatigue cycling at 130-lb maximum fatigue load. (Reinforced side loaded in tension.)

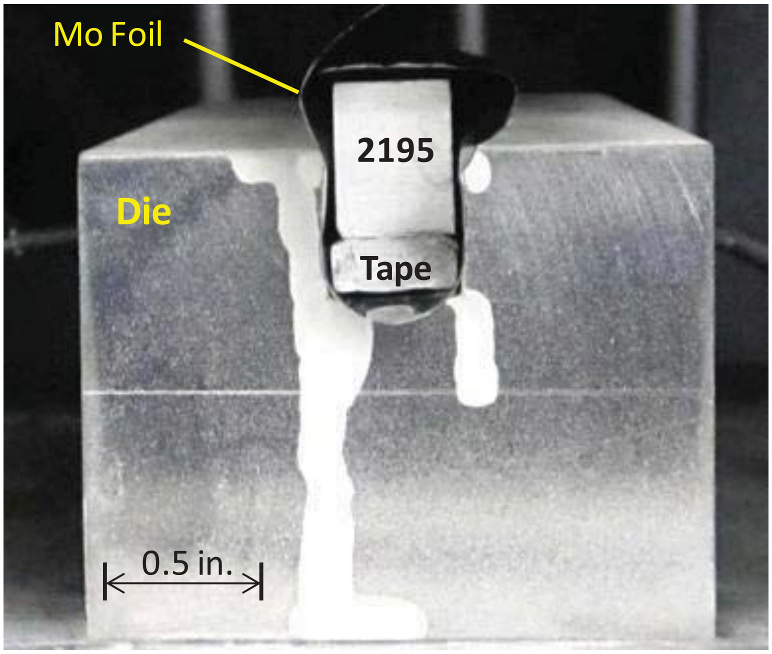

Figure 29. Photograph of end view of vacuum hot press set-up for simulating selective reinforcement of an Al-2195 stiffener (VHP-444).

Figure 30. Photograph of a simulated selectively-reinforced Al-2195 stiffener (VHP-444).

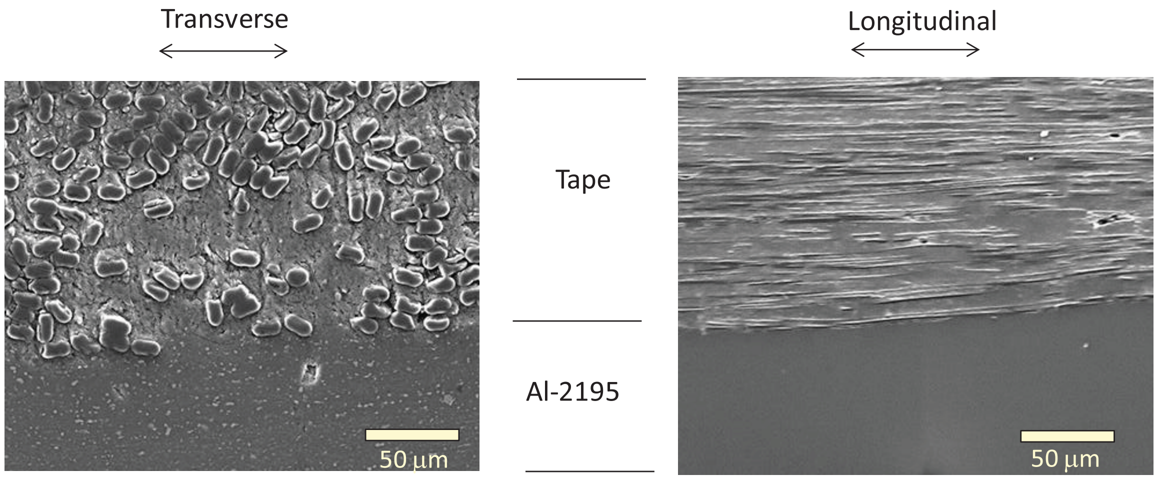

Figure 31. Electron photomicrographs showing the interface between the tape and stiffener for simulated selectively-reinforced Al-2195 stiffener (VHP-444).

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14. ABSTRACT
Several studies have indicated that selective reinforcement offers the potential to significantly improve the performance of metallic structures for aerospace applications. Applying high-strength, high-stiffness fibers to the high-stress regions of aluminum-based structures can increase the structural load-carrying capability and inhibit fatigue crack initiation and growth. This paper discusses an investigation into potential methods for applying reinforcing fibers onto the surface of aluminum and aluminum-lithium plate. Commercially-available alumina-fiber reinforced aluminum alloy tapes were used as the reinforcing material. Vacuum hot pressing was used to bond the reinforcing tape to aluminum alloy 2219 and aluminum-lithium alloy 2195 base plates. Static and cyclic three-point bend testing and metallurgical analysis were used to evaluate the enhancement of mechanical performance and the integrity of the bond between the tape and the base plate. The tests demonstrated an increase in specific bending stiffness. In addition, no issues with debonding of the reinforcing tape from the base plate during bend testing were observed. The increase in specific stiffness indicates that selectively-reinforced structures could be designed with the same performance capabilities as a conventional unreinforced structure but with lower mass.

15. SUBJECT TERMS
Aluminum alloys; Aluminum-lithium alloys; Bend tests; Fatigue; Reinforcing materials

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